Paul H. Moose, David Roderick*
Dept. of Electrical and Computer Engineering
Naval Postgraduate School
Monterey, CA. 93943
phmoose@nps.navy.mil

Richard North
SPAWAR System Center, San Diego, CA.

Michael Geile
Nova Engineering, Cincinnati, OH.

Abstract: A coded orthogonal frequency division multiplexed (COFDM) radio has been developed for high data rate (HDR) line-of-sight (LOS) communications in a mobile wireless network. COFDM has been chosen over more traditional single carrier adaptive equalization modulation techniques due to its better bandwidth efficiency and to its increased robustness to multipath fading and to interference. The radio is designed to operate in a burst mode, asynchronously exchanging radio frequency (RF) packets with other nodes in a wireless network. The data rate in each burst is optimized to provide the maximum data rate supported by the channel conditions. Four data rates are presently supported within a 600 KHz channelization; 1536 kbps, 768 kbps, 384 kbps, and 64 kbps. In addition, the radio may be operated in a synchronous continuous mode for broadcast or point-to-point applications.

I. INTRODUCTION

The HDR LOS wireless communications project at the U.S. Navy SPAWAR System Center, San Diego CA has developed a COFDM-based radio to implement a reliable ship-to-ship/shore/air mobile wireless network capable of supporting secure voice, data, and video services for the U.S. Military. The backbone data links have been designed to optimize the data rate (1536 to 64 kbps) of each RF packet burst within a fixed 600 KHz channelization (480 KHz occupied bandwidth) by adjusting the bandwidth efficiencies and spreading factor of the coded modulation. The wireless network will include self-configuring ad hoc topologies and automatic relaying to further extend the LOS communication ranges.

The heart of this system is a COFDM modem [1]. COFDM was chosen as the preferred modulation technique because of its excellent bandwidth efficiency, and its robustness in the mobile Military environment. COFDM has been used previously for the Asynchronous Digital Subscriber Loop (ADSL) [2] and the European Union Digital Audio Broadcast (DAB) [3] systems. Unlike these applications, this paper describes a COFDM modem design optimized for mobile wireless networks. The mobile wireless network requires that each mobile node send and receive RF packet bursts to and from multiple other mobile nodes. This mandates the use of omni-directional antennas. Communication range is maximized by transmitting in the VHF/UHF frequency bands[1] where bandwidth efficiency is critical to implementing a HDR system. Multipath fading can be severe between the mobile nodes in this environment. Previous research carried out by the HDR LOS Wireless Communications Project has identified three canonical UHF LOS channels typical for the maritime environment [4]:

a. UHF LOS Channel #1:
   - Propagation Loss = 135 dB
   - Path #1: Ricean, $F_d = 1$ Hz
   - Path #2: Rayleigh, $T_{1\text{-}2} = 0.01$ µsec, $F_d = 10$ Hz, $L_{1\text{-}2} = -6$ dB
b. UHF LOS Channel #2:
   - Propagation Loss = 135 dB
   - Path #1: Ricean, $F_d = 10$ Hz
   - Path #2: Rayleigh, $T_{1\text{-}2} = 0.07$ µsec, $F_d = 10$ Hz, $L_{1\text{-}2} = -5$ dB
   - Path #3: Rayleigh, $T_{1\text{-}3} = 0.80$ µsec, $F_d = 10$ Hz, $L_{1\text{-}3} = -15$ dB
c. UHF LOS Channel #3:
   - Propagation Loss = 135 dB
   - Path #1: Ricean, $F_d = 25$ Hz
   - Path #2: Rayleigh, $T_{1\text{-}2} = 0.9$ µsec, $F_d = 25$ Hz, $L_{1\text{-}2} = -3$ dB
   - Path #3: Rayleigh, $T_{1\text{-}3} = 5.1$ µsec, $F_d = 25$ Hz, $L_{1\text{-}3} = -9$ dB.

The Ricean channels have equal direct and multipath powers, F_d is the fade rate of each path, and $T_{k\text{-}j}$ and $L_{k\text{-}j}$ are the relative time delay and relative loss respectively between paths k and j.

This paper describes the results of research carried out to design the COFDM forward error correction coding, waveform, and frequency-timing recovery system. A waveform design is presented which supports reliable communication with bandwidth efficiencies greater than 3 bps/Hz. Two factors are found to contribute to packet loss; failure to acquire packet synchronization and uncorrected errors in the packet payload. The probability of packet loss is shown to be less than 1% in each of the three canonical UHF LOS Channels for each burst data rate. The COFDM-based radio is being built by Nova Engineering as a result of this research. The radio is estimated to provide reliable ship-to-ship communication ranges of 15 nmi, 18 nmi, 25 nmi, and 30 nmi at data rates of 1536 kbps, 768 kbps, 384 kbps, and 64 kbps respectively. Longer ranges are possible with favorable propagation conditions.

This work was funded by the Office of Naval Research code 313.
* Currently with Cypress Semiconductor, CA.

[1] Research is also being conducted in the HF band for intra-battlegroup communication using surface wave propagation for beyond LOS communication ranges.

II. MODEM ARCHITECTURE

The architecture of the HDR LOS modem is highlighted in Figs. 1 and 2. The modulation type, coding, spreading, and burst data rate for each of the four modes of operation is listed in Table 1. The characteristics of each successive mode was designed to give about 7 dB of improved performance over the previous mode while maintaining a data rate that is a multiple of a DS0 (64 kbps). Data to be transmitted is sourced by either the EIA-530 or the Ethernet serial interfaces. The data is structured into a MAC Protocol Data Unit (MPDU) by adding a medium access control (MAC) header and a frame check sequence (FCS) trailer. The MPDU is scrambled and encoded with a (225,205) Reed Solomon (RS) forward error correction (FEC) code. The RS code symbols are interleaved. For modes C and D (384 kbps and 64 kbps respectively), a rate ½k=7 convolutional inner FEC code is utilized. The coded bits are converted into OFDM modulation values, differential 16-PSK for the most bandwidth efficient mode (mode A) and differential QPSK for all other modes. The modulation values are interleaved and used to generate OFDM symbols using a 1024 point inverse FFT which are 0.500 milliseconds (ms) long including a 0.015 ms guard interval. Each OFDM symbol has 233 sub-carriers (232 for data plus 1 reference) spaced at 2.06 KHz. At the lowest data rate of 64 Kbps (mode D), the payload modulation values are replicated by a factor of five to spread their narrower spectrum over all of the 232 data sub-carriers.

Table 1: Data Modes for the COFDM Modem

	A	B	C	D
Data Rate (kbps)	1536	768	384	64
Modulation	16DPSK	DQPSK	DQPSK	DQPSK
RS Block Code	(225,205)	(225,205)	(225,205)	(225,205)
Conv. Code	-	-	R=1/2	R=1/2
Spread Code	-	-	-	R=1/5

The Physical Layer Data Unit (PLDU) is composed of a physical layer preamble, physical layer header, MDPU, and an end of message (EOM) as shown in Fig. 3. The preamble consists of one AGC symbol and one frequency timing recover symbol (FTR) and the header consists of three control symbols. The EOM consists of a single symbol. While the number of OFDM symbols in the MDPU is variable, the nominal value with respect to the UHF LOS canonical channels is greater than 100 (50 ms) to allow for adequate interleaving of the data throughout the PLDU.

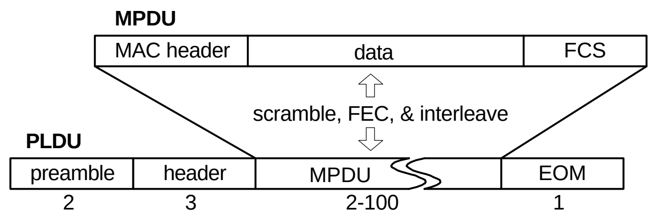

Fig. 3: Frame Structure of the MPDU and PLDU.

The receiver, shown in Fig. 2, is a dual diversity receiver with differentially coherent diversity combining. In order to receive a PLDU, the receiver must detect the preamble, remove any frequency offset that is introduced due to doppler and/or local oscillator offsets, and establish sample and symbol block timing for the OFDM demodulator and decoder. The FTR algorithms explained in Section V of this paper accomplish this. Following detection and synchronization, the received time-domain sample values corresponding to the PLDU are extracted and the symbols are demodulated in the OFDM demodulator. The OFDM demodulator removes the guard interval samples, computes the FFT of each of the blocks of symbol samples, and differentially decodes the phase of the received modulation values. The modulation values are coherently combined with those from the slave demodulator of the diversity channel and, for the 64 kbps mode D, coherently de-spread. The combined demodulation values are de-interleaved. The Viterbi convolutional decoder utilizes soft decisions for Modes C and D. After de-interleaving and decoding the

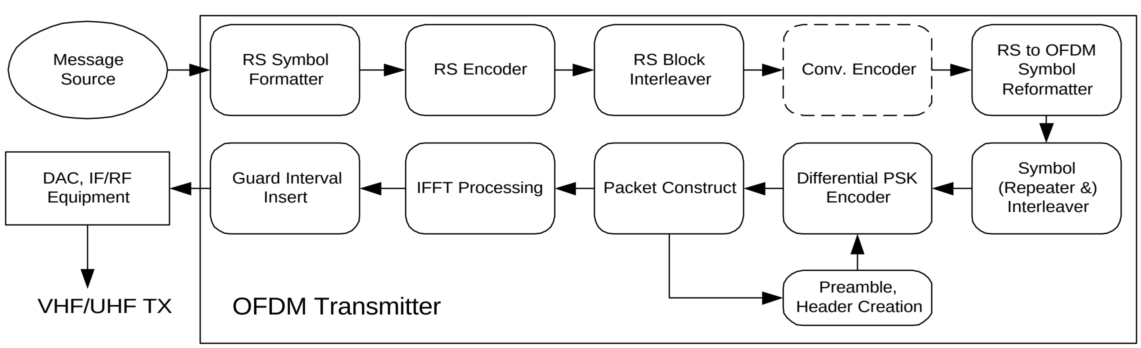

Fig. 1: OFDM Transmit.

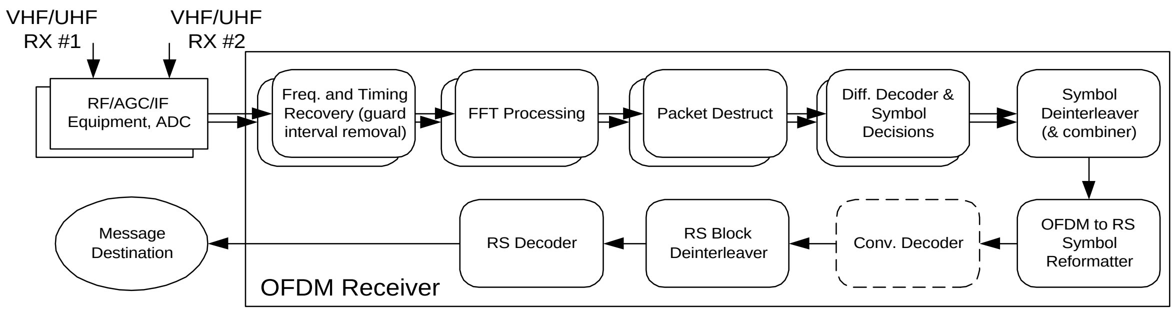

Fig. 2: OFDM Receive.

RS symbols, the MPDU is decomposed and the data is output via either the EIA-530 or the Ethernet serial data interfaces.

III. WAVEFORM DESIGN

OFDM represents an efficient method to transmit information in parallel in a frequency-selective channel. The addition of a short guard interval eliminates intersymbol interference (ISI). ISI normally limits the transmission rate in single carrier modulation methods. However, parallel transmission does not suppress the fading directly, since individual sub-carriers within the channel are affected by time varying fading. Coupling the inherent frequency diversity of OFDM with channel coding combines to give a high degree of protection to the transmitted data. Adding a second receive channel for spatial diversity makes the HDR LOS modem exceptionally robust even in the severe fading environments described above.

The OFDM waveform must be fully optimized in order to realize its benefits. Design of the waveform begins by choosing the length for the OFDM symbols. Symbols of 0.500 ms total length, with 0.015 ms allocated to guard interval and 0.485 ms allocated to the processing interval provide multipath protection to channels with up to 0.015 ms of time spread. The overhead associated with the 0.015 ms guard interval is only three percent. However, it is important that the symbol length be sufficiently short so that the channel is time-invariant over the length of the symbol. The maximum fade rate for the canonical channels is 25 Hz. Therefore, the channels should be quite stable for several milliseconds. Choice of the symbol length leads directly to the spacing and number of sub-carriers since the OFDM sub-carriers are spaced at the reciprocal of the processing interval. For a processing interval of 0.485 ms the sub-carriers are spaced at 2.06 kHz. Therefore, 232 sub-carriers, plus a reference sub-carrier for the differential coding, fits the HDR LOS OFDM waveform into 480 kHz of occupied bandwidth.

Differential PSK is selected as the preferred sub-carrier modulation format for simplicity. Although coherent 16-QAM or coherent QPSK have lower error rates for a given E_b/N_0, differential PSK renders the demodulation algorithm insensitive to the slow phase and amplitude variations of the channel. In OFDM, a choice exists between differentially coding the phases between sub-carriers within each OFDM symbol (frequency domain differential coding) and differentially coding each of the sub-carriers between successive symbols (time domain differential coding). Frequency domain coding requires that the sub-carriers be close enough together such that the phase of the channel is essentially the same for adjacent sub-carriers whereas time domain coding requires that the phase of each sub-carrier be essentially the same for two successive symbols. Frequency domain coding favors long symbols with close sub-carrier spacing whereas time domain coding favors short symbols.

Simulation tests for both types of differential coding were conducted to determine the optimum number of sub-carriers for 480 KHz bandwidth in the three canonical links described above. Five hundred different random number generator seeds were used to initiate the channel parameter variations and message data for each test. Each seed was used to transmit 10,000 OFDM symbols. Differential 16-PSK without FEC coding was used to conduct these tests. The results of the simulation tests for UHF LOS Channel #3 are shown in Fig. 4. It can be seen that frequency

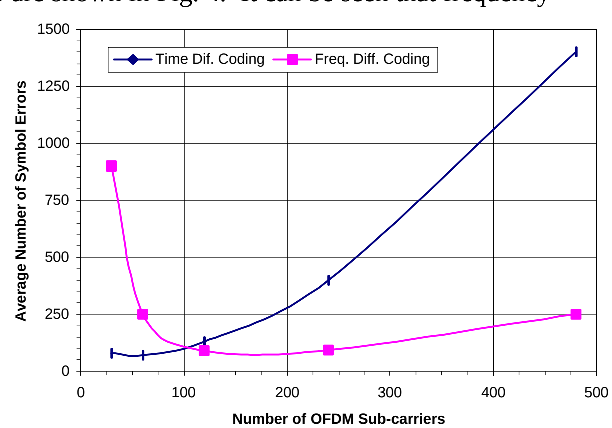

Fig. 4: Average symbol errors in 10,000 symbols versus number of OFDM sub-carriers in UHF LOS Channel #3.

domain differential coding is superior to time domain coding for more than 120 sub-carriers in this channel. Simulation tests for all three UHF LOS Channels led to the choice of 232 sub-carriers with frequency domain differential PSK as the best overall choice for the HDR LOS modem [5].

IV. PACKET LENGTH

Having selected an OFDM symbol length of 0.500 ms, the effect of PLDU length must be considered. From a wireless network viewpoint, variable packet lengths are desired to accommodate variable length data transmission requirements. However, in order for the FEC coding of COFDM to be effective, burst errors due to frequency and time selective fading must be redistributed randomly throughout the packet by interleaving. This means that the channel, which should not vary during an OFDM symbol, should vary substantially during a RF packet in order for the interleaving to be effective. For UHF LOS Channels #2 and #3, 50 ms RF packets (100 OFDM symbols) were determined by simulation to be sufficiently long that interleaving the entire RF packet randomized the fading induced errors enough so that the RS forward error control (FEC) coding is effective in their correction. UHF LOS Channel #1 varies so slowly that packets of nearly one second are required to make that link resistant to long persistent fades [5]. Such long packets introduce unacceptably long delays to the decoding process. Therefore, a spatially diverse second receive channel was incorporated into the HDR LOS modem to support the long flat fades associated with the UHF LOS Channel #1.

V. SYNCHRONIZATION

Synchronization of the sub-carrier frequencies and of the symbol timing is necessary in order to extract and decode the digital information from the OFDM payload packets. An efficient synchronization mechanism must require as few symbols as possible to achieve synchronization so that most of the symbols in the packet can be devoted to useful information. The HDR LOS modem packet detection and frequency/timing recovery system [6] requires just two OFDM symbols; one AGC symbol to bring the signal level within the dynamic range of the digital circuitry and one frequency/timing recovery (FTR) symbol. The FTR symbol and the recovery algorithm generate accurate timing and frequency information even in the presence of the severe frequency selective multi-path fading experienced in the canonical channels described previously and in additive noise down to a –5 dB signal-to-noise ratio.

The FTR symbol (FTR1) is sent as the second symbol in each packet. It is an ordinary OFDM symbol where each sub-carrier is DQPSK modulated with respect to each adjacent sub-carrier with random information. However, the information used to differentially modulate the sub-carriers is fixed and known at the receiver. Additionally, this symbol is constructed in such a way that the first half of the symbol is repeated during the second half of the symbol. This is accomplished by utilizing only every other OFDM sub-carrier. The payload symbols in the modem utilize 232 sub-carriers while FTR1 utilizes only 116.

At the receiver, all the sub-carriers may have been shifted up or down in frequency by an arbitrary amount due to Doppler shift and/or local oscillator offset. The receiver also does not know at what sample instant the packet will arrive nor does it know the beginning sample instant of the first and subsequent OFDM payload symbols. In order to demodulate and decode the information symbols, the receiver must shift the sub-carriers to their correct frequencies and commence the demodulation and decoding process for each symbol at their first sample instants.

Referring to Fig. 5, the HDR LOS modem derives the required synchronization information from the FTR symbol using an iterative process. During the first iteration a digital cross-correlator correlates between the first and second half of FTR1. The correlator operates on the incoming sample stream with a half symbol delay and an integration time of a half symbol. As the last sample value of FTR1 enters the correlator the correlation reaches a peak value because the first and second halves of FTR1 are identical. This peak is recognized by a peak detector and provides detection of the incoming packet and a first coarse estimate of symbol timing. The output of the cross-correlator at each instant consists of a magnitude and a phase value. The peak value whose occurrence provides a *coarse estimate* of timing is in fact a peak in the magnitude of the correlator output. The phase value of the correlator output at the instant of the peak measures the amount of frequency offset of the sub-carriers, modulo the frequency spacing of the sub-carriers. Thus, the phase of the correlator peak is a *fine estimate* of frequency offset.

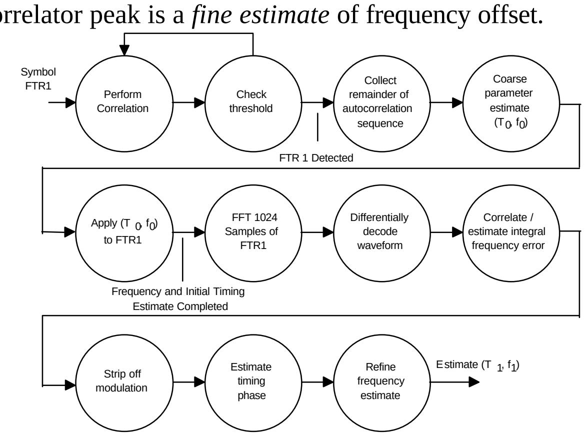

Fig 5: Processing flow for FTR.

A second iteration is performed, using the sample values from FTR1. The FTR1 sample values are frequency shifted by the fine frequency estimate obtained in the first iteration so that at this stage the residual frequency offset will be a multiple of the sub-carrier frequency spacing. The corrected symbol sample values are now demodulated using the receiver's OFDM demodulation circuitry consisting of the FFT and differential decoder to demodulate the encoded information between adjacent carriers. A cross-correlation function is now computed between this modulation information and the information known by the receiver to have been encoded into FTR1. The peak correlation occurs at an integer number corresponding to the number of sub-carrier frequency offsets that were left unresolved by the fine frequency offset estimate obtained during the first iteration. A total exact frequency offset has now been determined. The phase of the cross-correlation at the peak is used to determine any residual offset that is present in the sample timing. The resultant frequency and timing information is applied to the entire packet permitting demodulation and decoding of the OFDM signal.

The performance of the HDR LOS FTR algorithm has been shown to provide less than 20 Hz error (1% of the sub-carrier spacing) at SNRs down to –5 dB, which is acceptable for unimpaired OFDM demodulation of QPSK [7].

VI. PERFORMANCE

Fig. 6 illustrates the simulated BER performance of the modem with no spatial diversity for each of the four data rate modes described in Table 1 operating in AWGN. Eb/No for Mode D is calculated for each information bit in the channel. Because of the frequency diversity used in Mode D, each bit is in fact sent five times.

Simulated BER performance for each of the modes operating in UHF LOS Channels #1 & #3 (Section I) are shown in Figs. 7-10. Results for each mode include single diversity (D=1) and dual diversity (D=2) receivers. From these figures it can be seen that the link can be closed in all cases except Mode A, UHF LOS Channel #3. For Mode A, UHF LOS Channel #3, the RS FEC is not strong enough to remove all residual errors. The advantages of a dual diversity receiver are shown in Figs. 8 and 9 to reduce the required Eb/No 5 to 15 dB for Modes B and C. In Mode D, the inherent frequency diversity of the spread spectrum signal allows the single diversity receiver to perform as well in the multi-path channels (Fig. 10) as in AWGN (Fig. 6). The dual diversity receiver for Mode D provides 3 dB of gain regardless of the channel conditions. All elements of the modem including AGC, FTR and FEC are incorporated in these simulations.

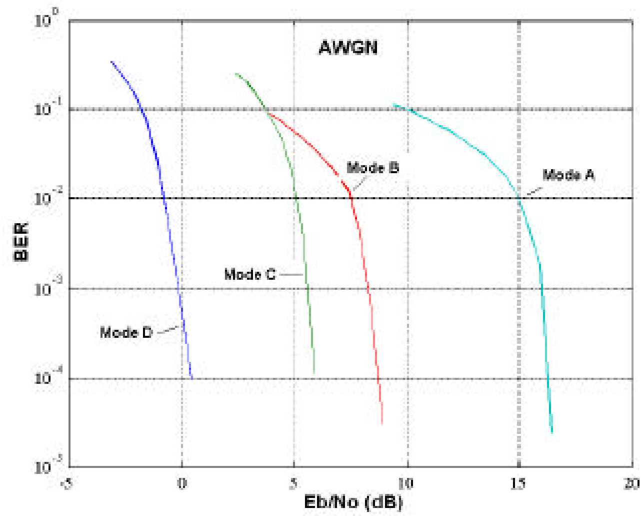

Fig. 6: BER versus SNR for AWGN.

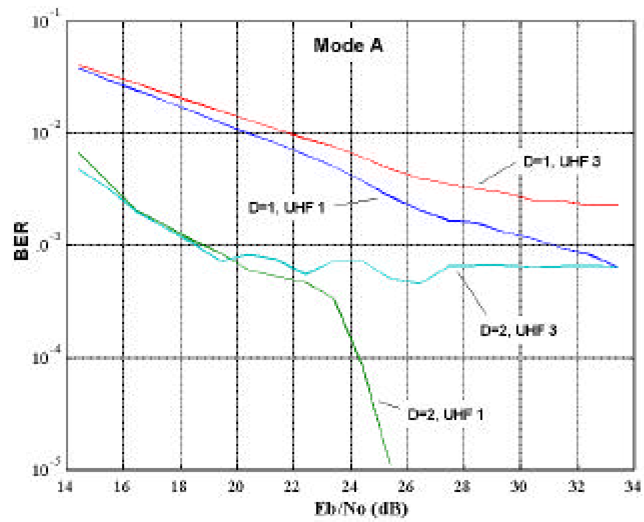

Fig. 7: Mode A BER versus SNR for Channels 1 & 3.

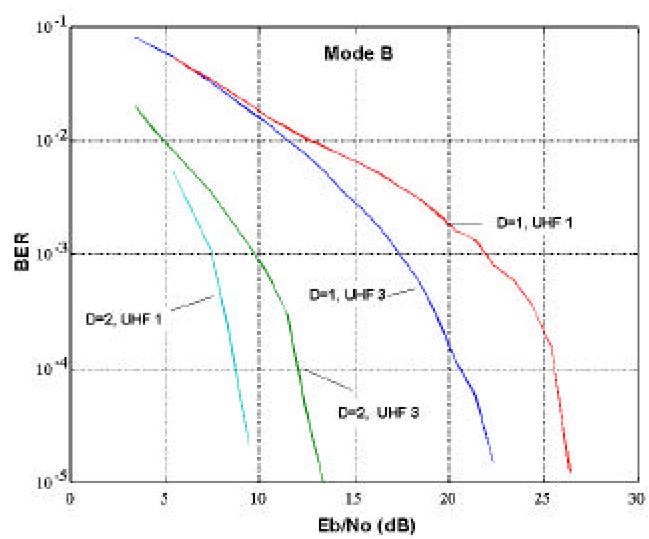

Fig. 8: Mode B BER versus SNR for Channels 1 & 3.

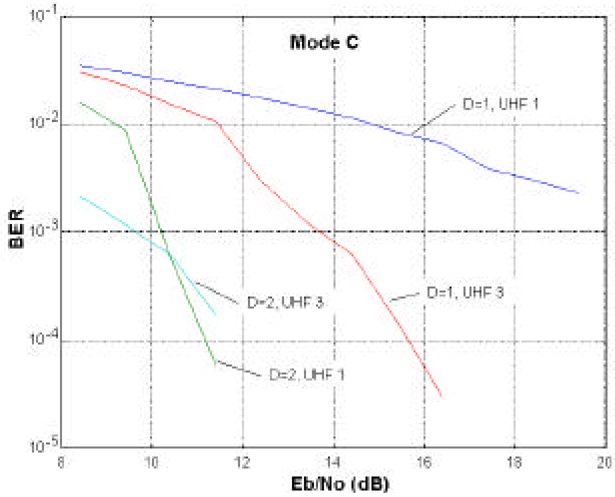

Fig. 9: Mode C BER versus SNR for Channels 1 & 3.

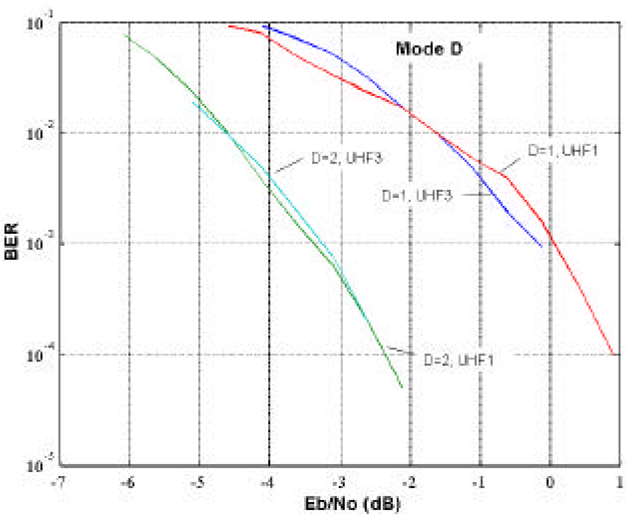

Fig. 10: Mode D BER versus SNR for Channels 1 & 3.

VII. SUMMARY

The HDR LOS wireless communications project at the U.S. Navy SPAWAR Systems Center in San Diego, CA. has conducted research over the last several years to establish the characteristics of mobile maritime channels in the Military UHF frequency band and to develop a digital radio to support Naval Battle Groups and Amphibious Readiness Groups in this environment. The heart of the HDR LOS radio is a COFDM modem used to asynchronously exchange RF packets among nodes of the wireless network. The modem operates on a 600 KHz channelization with 480 KHz of occupied bandwidth. It utilizes 232 sub-carriers spaced at 2.06 KHz each differentially PSK encoded in the frequency domain. It has four data rate modes, 1.536 Mbps, 768 kbps, 384 kbps and 64 kbps which are obtained by varying the number of bits in the PSK constellations, the strength of the FEC code, and the spectrum spreading factor. The radio supports nominal ranges of 15 miles at 1.536 Mbps and in excess of 30 miles at 64 kbps.

An important feature of the HDR LOS radio is fast acquisition of the RF packets. Packet detection and frequency and timing synchronization are accomplished using just two OFDM symbols. The basis for the FTR circuitry is a differential cross-correlator for packet detection followed by frequency domain processing of the FTR symbol using the modem's embedded OFDM demodulator to obtain accurate symbol timing and frequency offset information. The detection and synchronization circuitry operates without impairment to the modem's error performance at input signal-to-noise ratios down to –5 dB even in the severe multipath channels of the maritime environment.

Other variations of COFDM are being researched. Both a wider band version that can support higher data rates and a version to support 64 kbps in a 25 kHz channelization are being pursued. In addition, predistortion techniques are being investigated to partially compensate for amplifier non-linearities and further improve the system gain. The HDR LOS radio hardware being built by Nova Engineering is designed to support full-duplex operation with dual diversity reception at data rates up to 4.608 Mbps. Finally, various types of network and media access channel protocols are being investigated to complete a wireless networked radio supporting voice, data, and video applications for mobile Military platforms.

REFERENCES

[1] B. Le Floch, M. Alard and C Berrou, "Coded orthogonal frequency division multiplex", **Proc. of IEEE,** Vol. 83, No. 6, June 1995.

[2] J. Chow, J. Tu and J.M. Cioffi, "A discrete multitone transceiver system for HDSL applications," **IEEE J. on Selected Areas in Commun.,** Vol SAC-9, Aug. 1991.

[3] B. Le Floch et. al., "Digital sound broadcasting to mobile receivers," **IEEE Trans. Consum. Elec.,** Vol. 35, No. 3, Aug 1989.

[4] http://bobcat.spawar.navy.mil/hdrlos/index.htm

[5] D. V. Roderick, "A coded orthogonal frequency division multiplexing simulation of a high data rate, line of sight, digital radio for mobile maritime communications", Electrical Engineers Thesis, **Naval Postgraduate School,** June 1997.

[6] P. Moose, M. Geile, R. North, "Frequency and timing recovery for synchronization of OFDM digital communications signals," U.S. Patent applied for, Sept. 1998.

[7] P. Moose, "A technique for OFDM frequency offset **IEEE Trans Commun.,** Vol 42, No. 10, Oct. 1994.